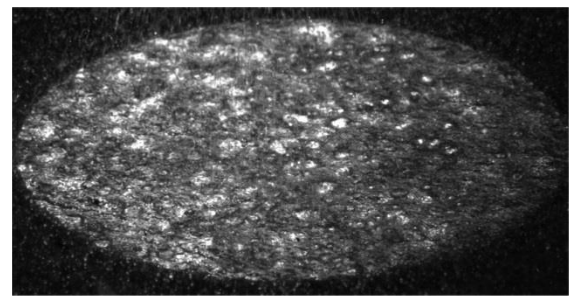
THERMAL & FLUIDS ANALYSIS WORKSHOP

GSFC · 2015

# New Data for Improvement of a Monte Carlo Model of Spray Cooling



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# Introduction/Overview

- **Cooler spray droplet liquid in close contact with the heated surface beneath the drop impact cavities contributes to high local heat fluxes, due to increased transient conduction.**
- **We have been <u>studying spray droplet impact</u> onto 5 cm dia. smooth, unheated surface.**
- **<u>Spray Data</u> (water from a Spraying Systems 1/8-G full-cone nozzle):**
  - **a.) Phase Doppler Particle Analyzer (PDPA): droplet (*d*, *V*)**
  - **b.) Residual liquid layer thickness on impact surface, *h***
  - **c.) Spray droplet impact cavity diameter, $D_{cavity}(t)$**
- **Also, <u>we have studied single droplet impacts</u>, to document the sub-cavity volumes vs. time. (To estimate heat flux to dry out the sub-cavity volume in cavity lifetime.)**
- **<u>Single Droplet Data</u>:**
  - **a.) Thickness of thin liquid film beneath the drop impact cavity, vs. time and radius**
  - **b.) Cavity lifetime**
  - **c.) Sub-cavity liquid volume, vs. time, for ranges of *We*, *Re*, and *h*/*D* relevant to sprays**
- **This data, along with CFD simulation results, to be used in a simplified Monte-Carlo model of the spray cooling process (Kretizer, 2010; Kuhlman *et al*., 2011)**

# Background on Spray Cooling

- Active cooling techniques needed when uniform, low surface temperature and high heat flux are desired. (E.g., for high-end supercomputers, laser diode arrays)
- Spray cooling has demonstrated heat fluxes of 500-1000 W/cm$^2$ for water as coolant (Lin & Ponnappan, 2003; Pais *et al*., 1992), & relatively low surface temperature. (E.g., heat fluxes of 100 W/cm$^2$ at surface temps. of $(T_{wall} - T_{sat}) \approx 10K$)
- Sprays are too complex for full CFD simulation; experiments also take too long for use in design optimization.
- A full understanding of interaction between the complex physical processes in spray cooling, across wide ranges of time & length scales, is lacking.
- Problems for practical applications: phase separation in closed-loop systems; nozzle clogging or erosion, large surface areas.
- The preliminary Monte Carlo model developed by Kreitzer (2010) shows promise.
  - Goal: Accurate heat flux prediction for given spray conditions & heater surface geometry.
  - Incorporates time scales from dimensional arguments, & empirical correlations from experiments & CFD simulations.
  - This model is qualitatively promising, but NOT quantitatively accurate.

# Time Scales for Monte-Carlo Model

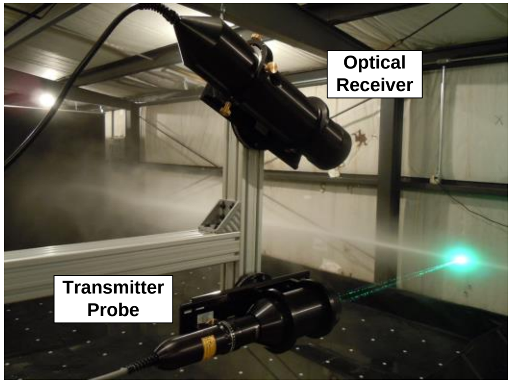
- **Droplet-heater surface interaction time:** $t_i = \dfrac{D}{V}$
- **Cavity growth time*:** $t_{cg} = 12.5t_i$
- **Capillary wave velocity:** $v_{capillary} = \left(\dfrac{\sigma}{\rho h}\right)^{0.5}$
- **Time for capillary wave to fill in cavity:** $t_{cf} = \dfrac{R_c}{v_{capillary}}$
- **Total cavity lifetime:** $t_{ct} = t_{cg} + t_{cf}$
- **Time for cavity to be covered by neighbor:** $t_{cover} = \left(\dfrac{Vol_d}{Q}\right)\left(\dfrac{A_{heater}}{A_{cavity}}\right)$
- **Time scale for cavity to dry out:** $t_{dry} = \dfrac{\left[m_c C_p (T - T_{sat}) + m_g h_{fg}\right]}{q'' A_{cavity}}$

*Sivakumar & Tropea, 2002; see their Figure 3.

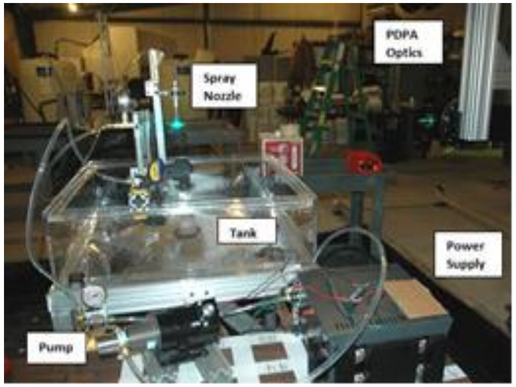
(These time scales were first proposed by Kuhlman *et al.*, 2007)

# PDPA Measurements for Sprays

- Two-component TSI PDPA system: 5 W argon-ion laser & multicolor beam generator. Optics configured in 30° off-axis backscatter mode, mounted on a tri-axis traverse.
- Spraying Systems 1/8-G full cone spray nozzle.
- Data obtained both with and without 5 cm diameter smooth, unheated surface (Hillen, 2013).
- Nozzle pressures:  1.4, 2.8, and 4.1 bar, for nozzle standoff  distances:  32, 38 & 45 mm.



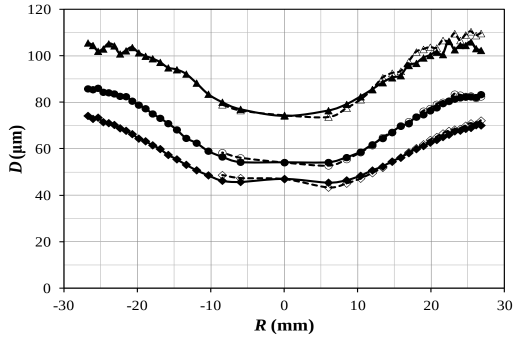

**PDPA optics in backscatter mode**



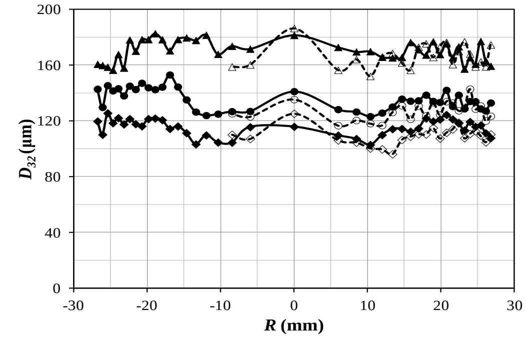

**Spraying Systems 1/8-G nozzle**

# PDPA Spray Measurements

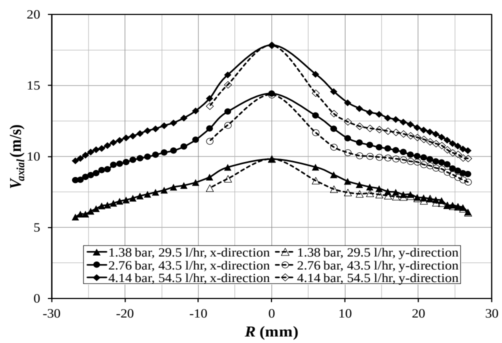
**PDPA data for Spraying Systems 1/8-G nozzle, no impact surface 38 mm standoff:**



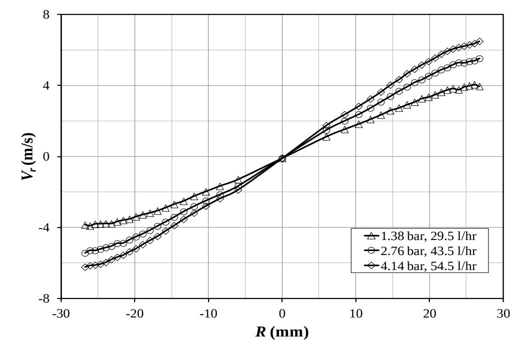

**Droplet average diameter, *D***




**Sauter mean diameter, $D_{32}$**



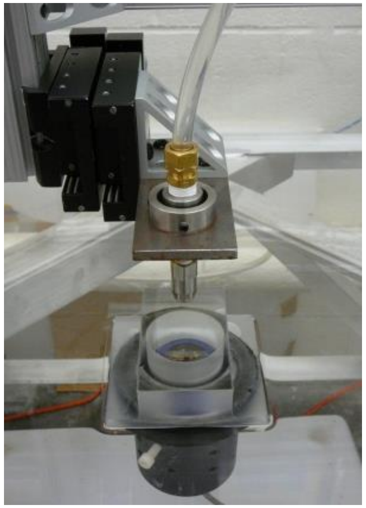

**Droplet mean axial velocity, $V_{axial}$**



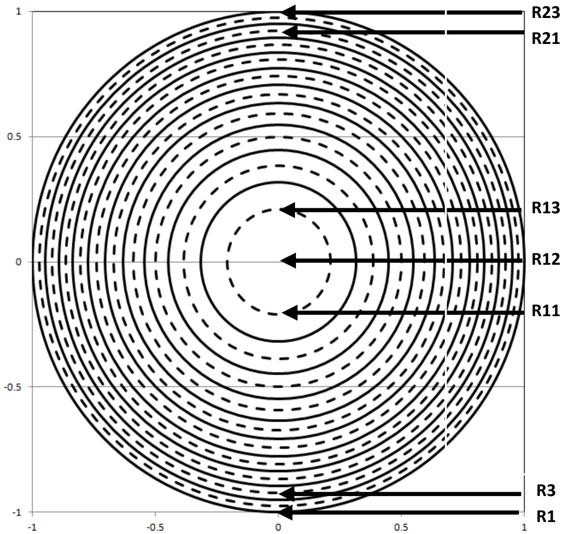

**Droplet mean radial velocity, $V_r$**

- **These data were used to set ranges of (*We*, *Re*) for the single-drop test matrix.**

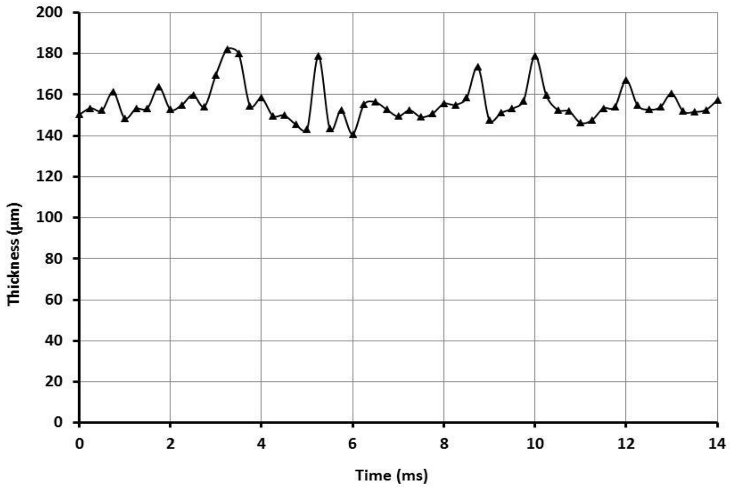
# Film Thickness Measurements for Impacting Sprays



Spray nozzle & CHR sensor



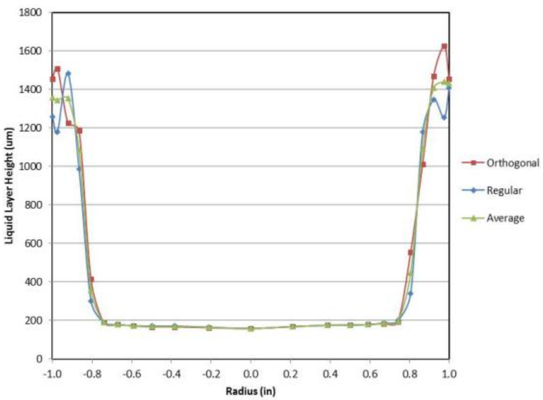

Radial measurement locations



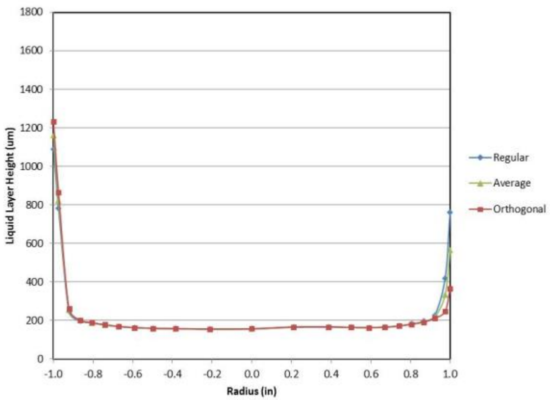

Sample of data time series: $p$ = 4.1 bar, at R12

- **Spraying Systems 1/8-G full cone spray nozzle, same 3 nozzle pressures, only at nozzle standoff distance of 38 mm. (left image)**
- **Confocal chromatic optical thickness "CHR" sensor developed by Precitec used to measure liquid film thickness. (left image)**
- **Spray impacted normal to 5.1 cm by 10.1 cm unheated glass impact plate, glued to Plexiglas base with 5 cm hole for CHR sensor to view from below. (left image)**
- **CHR sensor has full range of 3 mm, resolution of 0.1 µm, at 4,000 samples/sec. (right image)**
- **Impact spray film thickness measured at 23 radial locations at centroids of annular areas having equal-areas. (center image).**

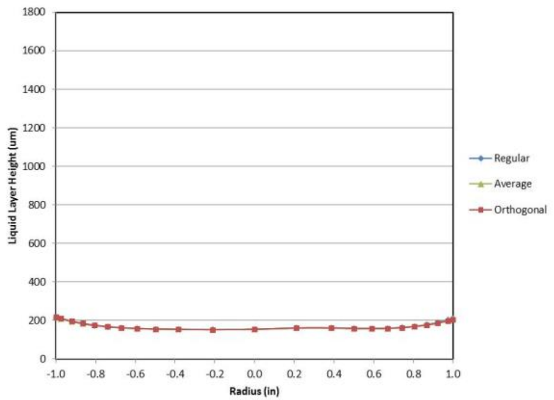
# Measured Avg. Liquid Film Thickness vs. Radius




Nozzle pressure, $p$ = 1.4 bar



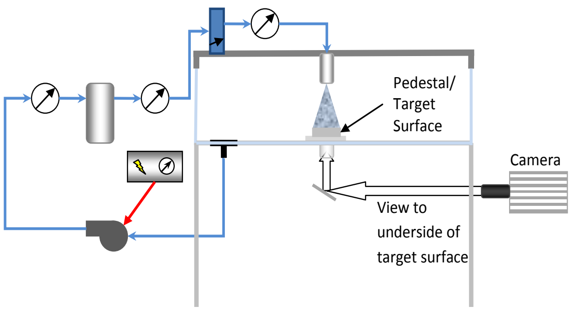

Nozzle pressure, $p$ = 2.7 bar



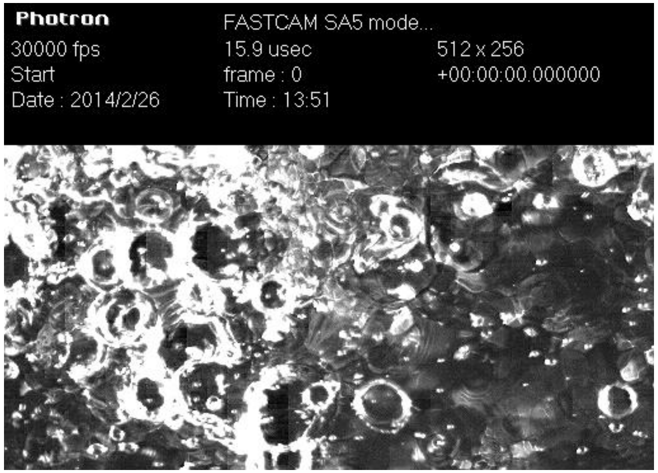

Nozzle pressure, $p$ = 4.1 bar

- **Main result: average liquid film thickness is approximately $h$ = 160 $\mu$m**
- **This residual liquid film thickness is in the range of values in the literature.**
- **Spray cone angle increases as nozzle pressure increases; 5 cm diameter disk is "well covered" by spray at $p$ = 4.1 bar, but hydraulic jump due to low spray flux occurs at large radius at both lower pressures.**

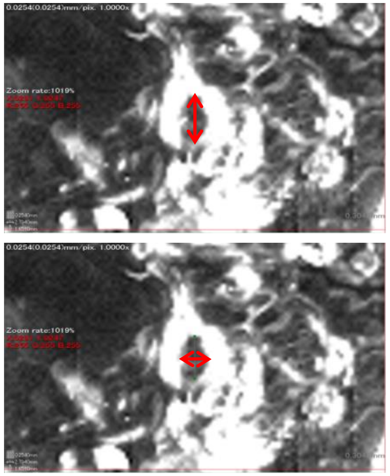
# Spray Droplet Impact Cavity Diameter vs. Time




HS video imaged from below



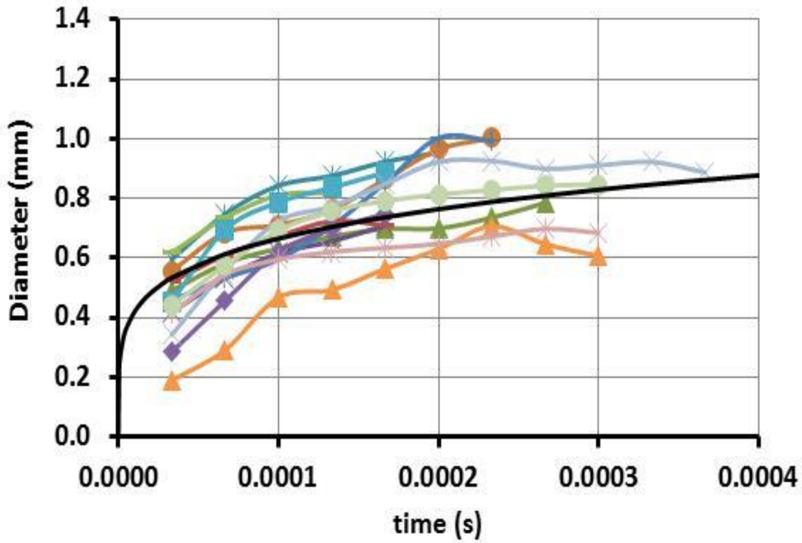

Sample video: $p$ = 1.7 bar, at $R$ = 22.5 mm



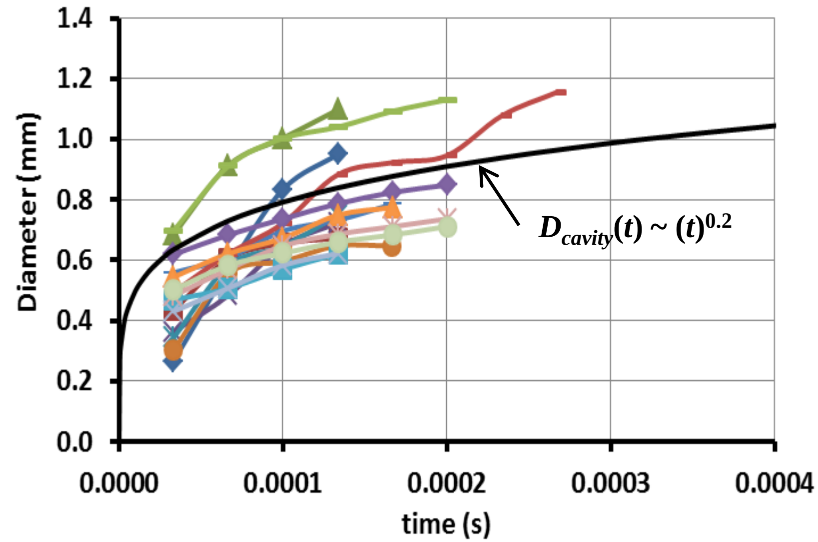
Zoomed image, showing vert. & horiz. cavity $D$ values

- Spraying Systems 1/8-G full cone spray nozzle, at same 3 nozzle pressures of 1.4, 2.7, and 4.1 bar, at nozzle standoff distance of 38 mm. (left image)
- Spray impacts normal to 5.1 cm by 10.1 cm unheated glass impact plate.
- Viewed from beneath transparent impact surface, w backlighting from above (left image).
- Camera frame rate of 30,000 fps, with pixel resolution of 512 x 256 pixels (center image).

# Spray Droplet Impact Cavity Diameter vs. Time



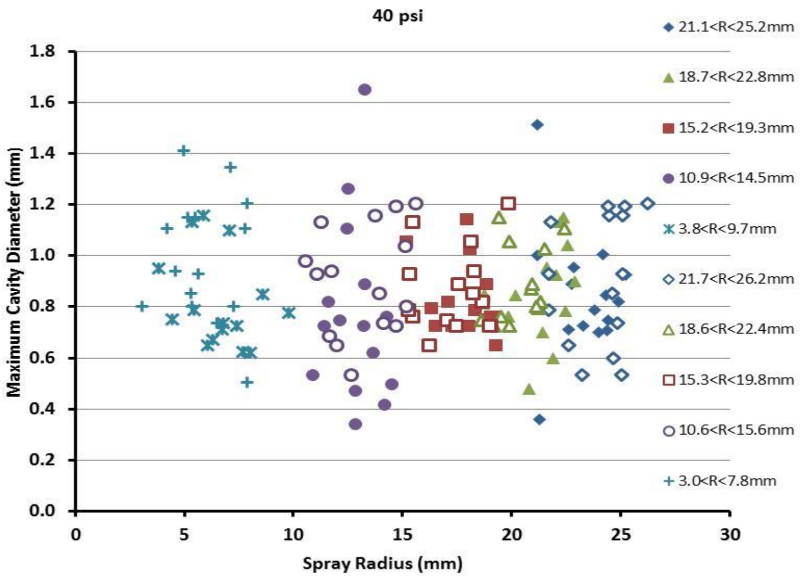

Small radius (3.8 mm < R < 9.7 mm)



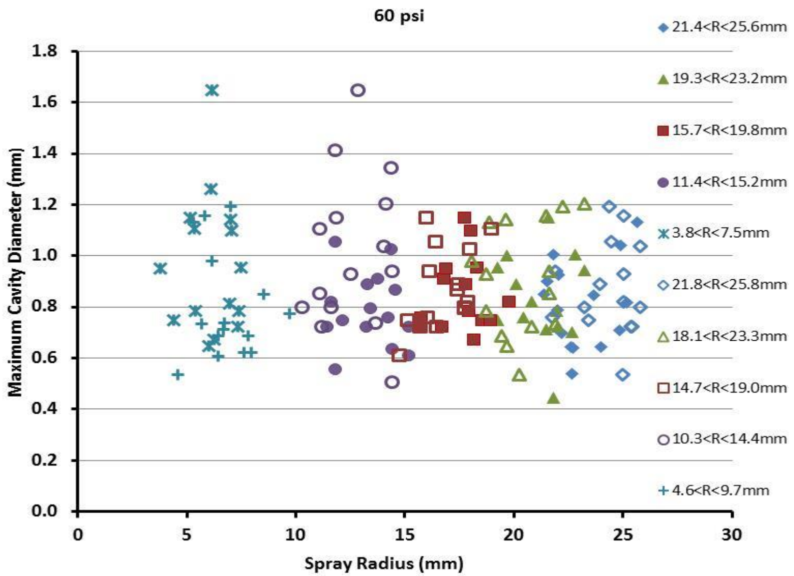

Large radius (21.1 mm < *R* < 25.2 mm)

- These results obtained at nozzle operating pressure of $p$ = 2.7 bar (Taylor, 2014).
- Cavity radius for impacting spray drops is well-correlated by a power law variation of $R_{cavity}(t) \sim (t)^{0.2}$.
- This differs from isolated droplet results: $R_{cavity}(t) \sim (t)^{0.5}$.
- Sivakumar & Tropea (2002) also found $(t)^{0.2}$ variation for their hollow-cone spray.
- Generally, we cannot observe the cavity diameter during the retraction phase.
- Estimated time to maximum cavity diameter is around 200 $\mu$s. (Estimate 400 $\mu$s = cavity lifetime?)

# Maximum Cavity Diameter vs. Radial Impact Location




Nozzle $p$ = 2.7 bar




Nozzle $p$ = 4.1 bar

- **Most maximum cavity diameters range from 0.3 mm to 1.6 mm.**
- **Assuming cavity maximum diameter to be 5 times the droplet diameter leads to estimates of droplet diameters of from 60 $\mu$m to 320 $\mu$m, consistent w PDPA data.**
- **Maximum cavity diameter does not change vs. the radial impact location, or vs. operating pressure.**

# Time Scales: Comparison with Spray Results

- **Use the simple time scale estimates from above to attempt to predict an average drop impact cavity lifetime, etc.**
- **Assume nozzle flowrate of $Q$ = 10 GPH = 1.05 x $10^{-5}$ $m^3/s$, an (average) drop diameter of $D$ = 100 $\mu$m, a residual liquid layer thickness of $h$ = 160 $\mu$m, and $V$ = 10 m/s.**
- **Assume spray liquid to be water, and that the maximum cavity diameter is 5 times the droplet diameter (Sivakumar & Tropea, 2002).**
- **Then time scales are:** $t_i = \frac{D}{V}$ **= $10^{-5}$ s, so** $t_{cg} = 12.5 t_i$ **= 125 $\mu s$**

$$v_{capillary} = \left(\frac{\sigma}{\rho h}\right)^{0.5}$$ **= 0.675 m/s, so then with $R_c$ = 2.5 $D$**

$$t_{cf} = \frac{R_c}{v_{capillary}}$$ **= 370 $\mu s$, so finally:**

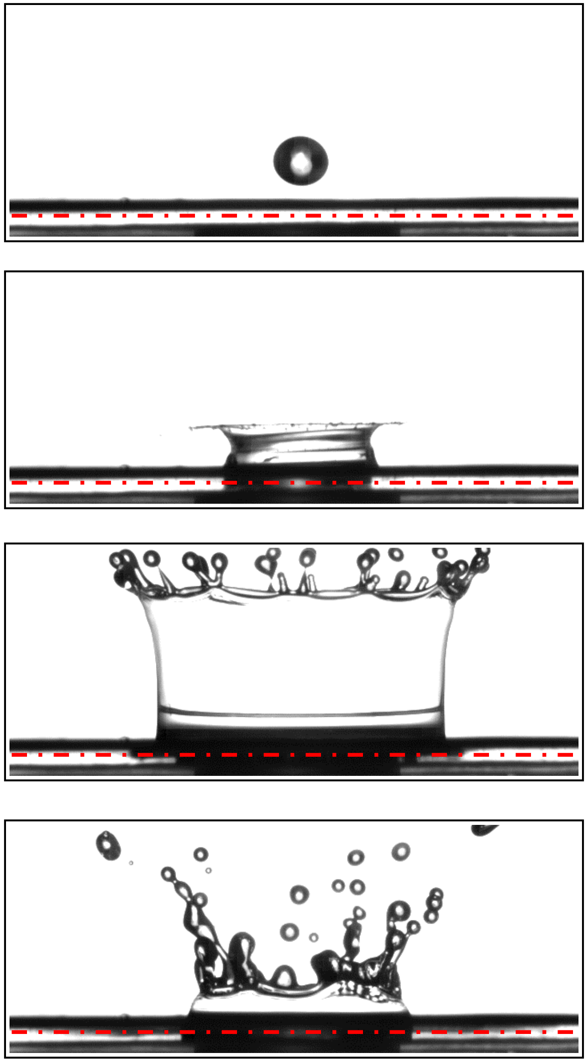
**total cavity lifetime = $t_{cg} + t_{cf}$ = <u>495 $\mu s$</u>**

- **Also, time for cavity to be re-covered or filled in by subsequent, nearby drop impacts is:**

$$t_{cover} = \left(\frac{Vol_d}{Q}\right)\left(\frac{A_{heater}}{A_{cavity}}\right)$$ **= <u>500 $\mu s$</u>, using 5.08 cm as heater dia.**

- **These time scales both are close to estimated cavity lifetime of ~<u>400 $\mu s$</u> from the HS video.**

# Single Drop Sub-cavity Experiments

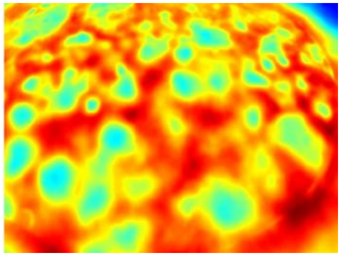


# Motivation

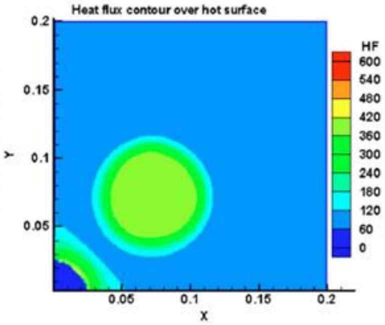
- **Kuhlman *et al*. (2007): sub-cavity volume should enhance spray cooling heat transfer. (Cooler droplet liquid in close contact w heated surface beneath drop impact cavities leads to higher localized transient wall heat fluxes.)**

- **Existing evidence: 1.) Soriano *et al*. (2010) saw highest wall-normal temperature gradients at drop impact point, & simulations by Gehring *et al*. (2010) showed the cooler drop liquid penetrated the liquid film to the surface.**

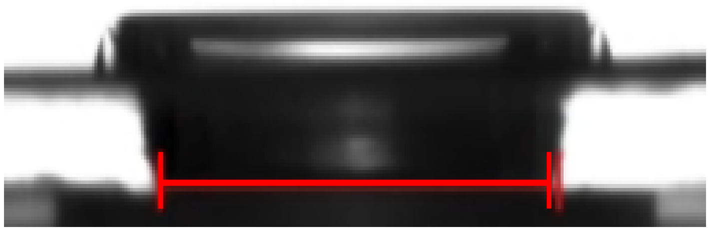
**2.) Experiments by Kyriopoulos (2010): spray droplet impact cavity liquid significantly cooler than residual liquid; see IR Camera image: (cooler liquid seen in impact cavities)**



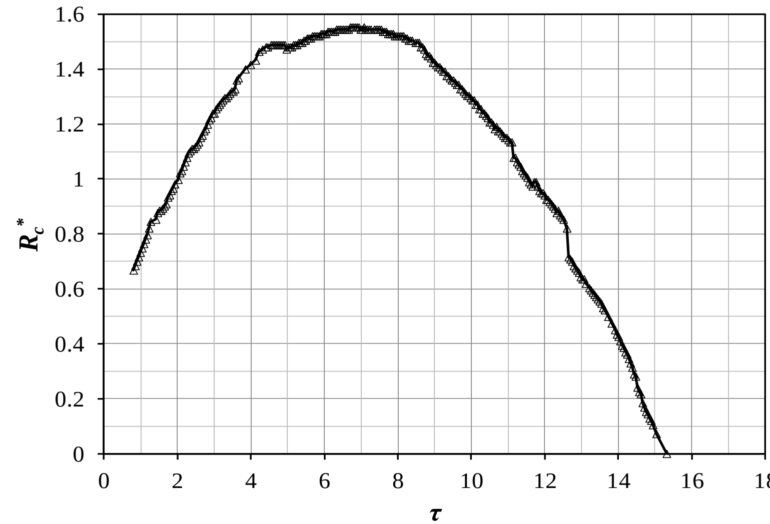
**3.) Single drop 3-D CFD simulations of Sarkar & Selvam (2009) showed sub-cavity wall heat flux was about 4-6 times higher than the heat flux in surrounding liquid layer.**



# Single Drop Sub-Cavity Diameter vs. Time



**One sample cavity side-view diameter (red line shows measured cavity diameter)**

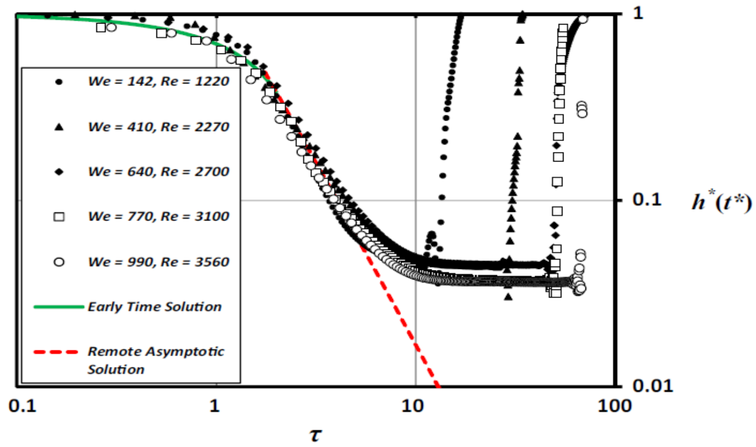



**Side-view dimensionless cavity radius vs. dimensionless time.**

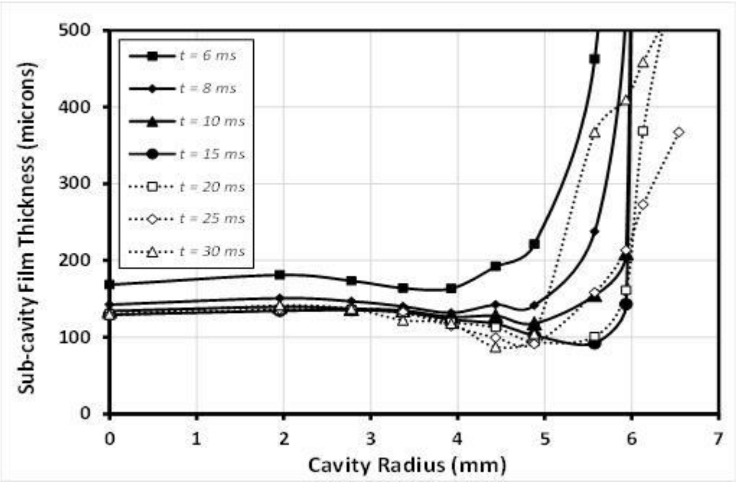
**This data was used to determine radial locations to measure sub-cavity liquid film thickness using Precitec confocal chromatic optical thickness "CHR" sensor.**

**This thickness data (below) was then integrated radially at each time to compute sub-cavity liquid volumes vs. time (Hillen, 2013).**

# Single Drop Sub-Cavity Film Thickness vs. Time & *R*



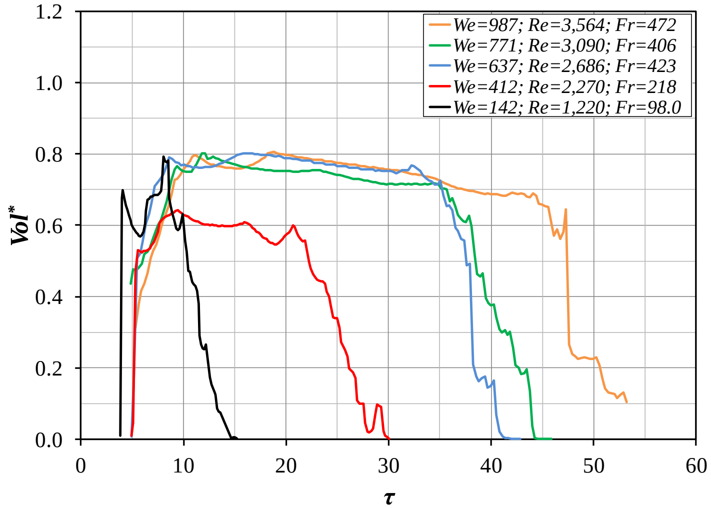

Centerline cavity film thickness vs time, for all 5 *We* values, between 142 to 990 at *h*/*D* = 1.0, from Hillen & Kuhlman (2015).



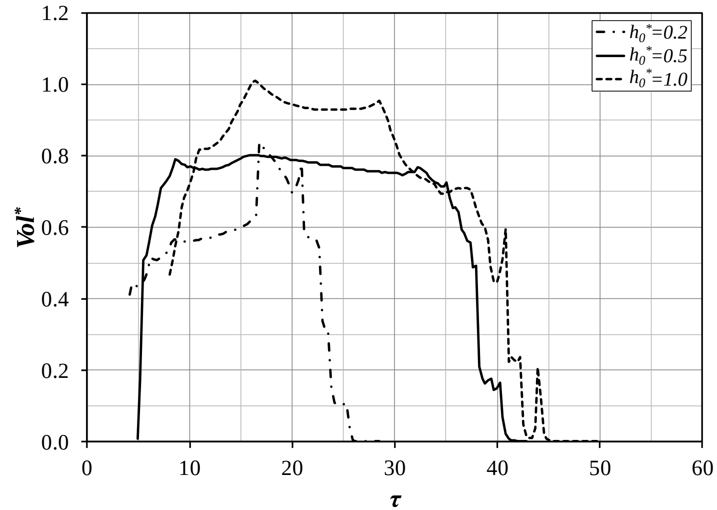

Radial cavity film thickness data, at several times between 6 ms and 30 ms, at *We* = 412, *h*/*D* = 0.5.

- Time to establish thin centerline film value is nearly independent of *We*, and minimum film thickness decreases only slightly as *We* increases (left plot). Also, cavity lifetime increases significantly as *We* increases (left plot).
- Local cavity film thickness decreases somewhat near inner crown wall at each time (right plot), especially at later times shown (during & just prior to crown collapse).
- These data have been integrated radially to compute the sub-cavity liquid volume vs. time (Hillen, 2013)

# Single Drop Results: Sub-Cavity Volume vs. Time



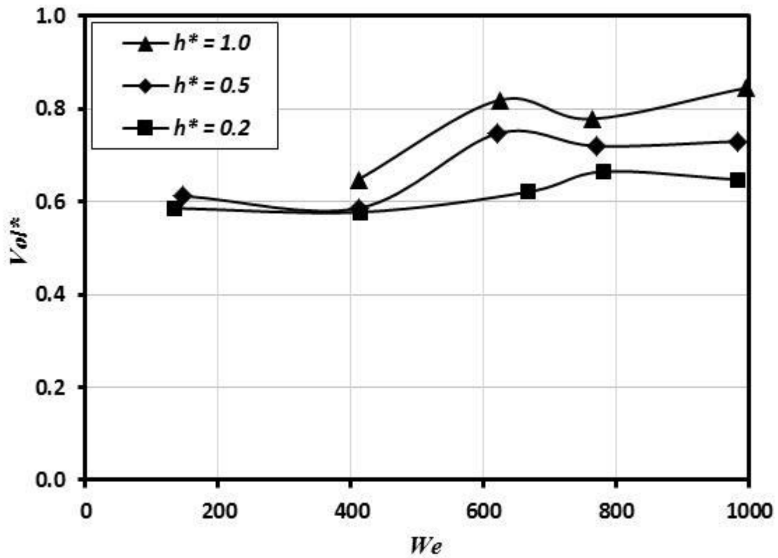

**Variation vs. *We***
**Constant: $h_0^* = 0.5$**

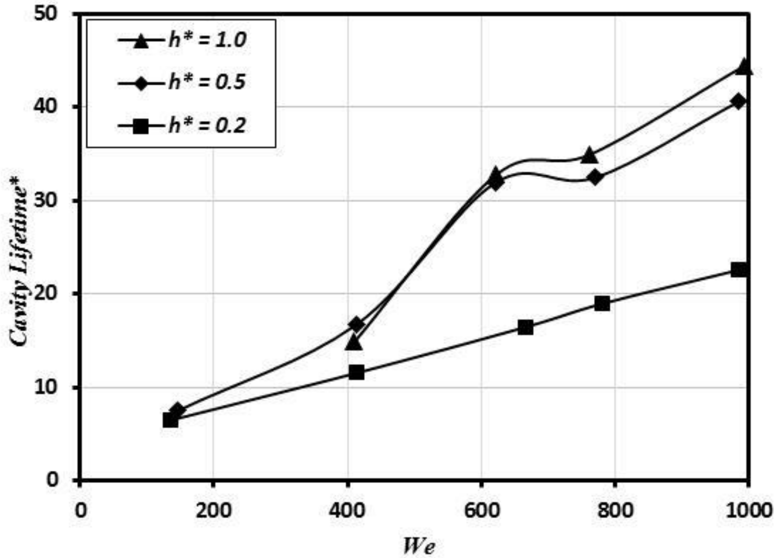



**Variation vs. $h_0^*$**
**Constant: *We* = 637; *Re* = 1,217; *Fr* = 142**

- ***Vol**** **= (sub-cavity volume)/(drop volume); also, $\tau = t/(D/V)$.**
- **Computed sub-cavity volumes are relatively constant for much of cavity lifetime.**
- **Sub-cavity volume increases with both *We* and $h^*$ (between $h^* = 0.2$ and 1.0), but effect of increasing *We* is reduced for *We* above ~600**
- **Sub-cavity lifetimes also increase with increasing $h^*$ and *We*.**
  - **Effects of *We* on lifetimes more pronounced than $h^*$.**

# Average Sub-Cavity Volumes and Cavity Lifetimes




- **The sub-cavity liquid volume has been computed as the average value of $Vol_c$ for times where $Vol_c^*$ is above 0.5; also, this time is taken as the cavity lifetime.**
- ***Vol** = (sub-cavity volume)/(drop volume)***
- **The (*Cavity Lifetime*)* increases as either *We* or *h** are increased (see right plot).**
- **The average *Vol** increases somewhat as either *We* or *h** are increased (left plot).**
- **Sub-cavity liquid volume primarily between 60% - 80% of droplet volume (left plot).**

# Compute Cavity Heat Flux to Dry Out the Cavity

- **Use the measured cavity lifetimes and sub-cavity liquid volumes to compute the heat flux to dry out cavity.**
- **A simple energy balance between the heat conducted through the heated surface to dry out the sub-cavity liquid volume is (time scales in slide 4):**

$$t_{dry}\,(q_w'')_{dry}\,A_c = \rho Vol_c[C_p\,(T - T_{sat}) + h_{fg}] \qquad (1)$$

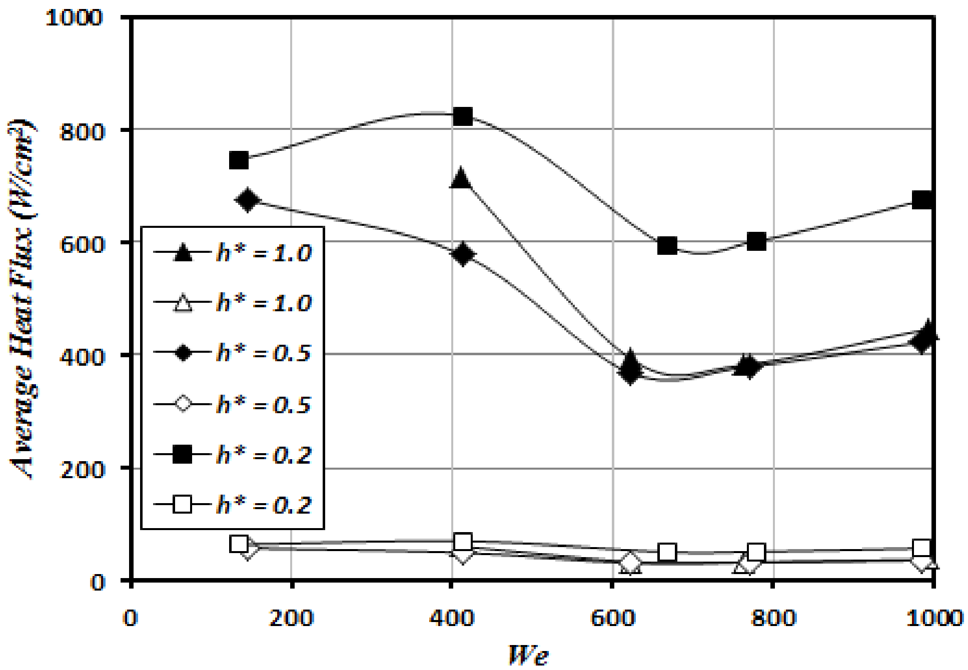
- **To estimate the required cavity average wall heat flux to boil away all of the sub-cavity liquid volume during the sub-cavity lifetime:**

$$(q_w'')_{dry} = \rho Vol_c[C_p\,(T - T_{sat}) + h_{fg}]/(A_c t_{cavity}) \qquad (2)$$

**where $t_{cavity}$ now is the sub-cavity lifetime.**

- **The dimensional single-drop $Vol_c$ values were rescaled for spray drops by the factor, $(D_{spray}/D_{1\text{-}drop})^3$.**
- **The measured single-drop $t_{cavity}$ were rescaled by $(D_{spray}/V_{spray})/(D_{1\text{-}drop}/V_{1\text{-}drop})$.**

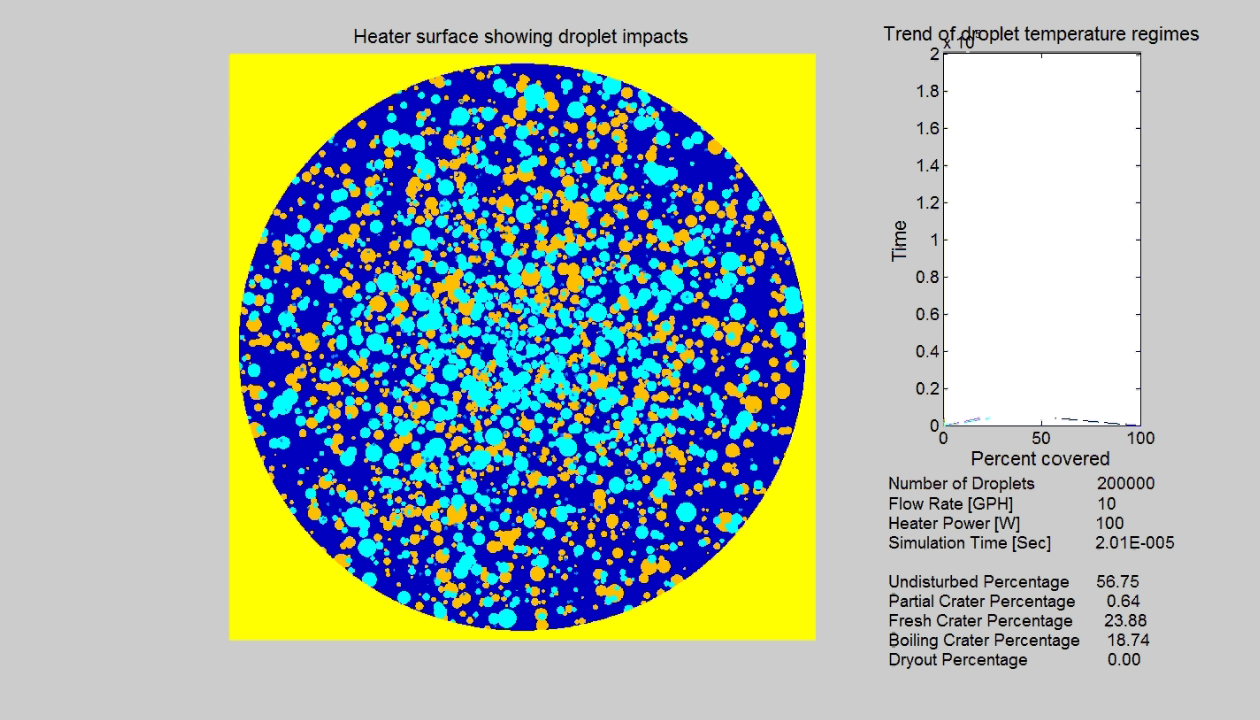
# Computed Avg. Heater Heat Flux to Dry Out Cavity




- **<u>Filled symbols</u> are the predicted $q_w$" for <u>cavity dry out to occur</u> within cavity lifetime, using equn. 2.**
- **The computed $q_w$" values for cavity dry out above are in the range of $q_w$" for CHF for water as coolant from literature (order of 500 -1000 W/cm$^2$: Lin & Ponnappan, 2003; Pais *et al*., 1992).**
- **<u>Open symbols</u> are predicted $q_w$" for <u>onset of boiling</u> within sub-cavity volume.**

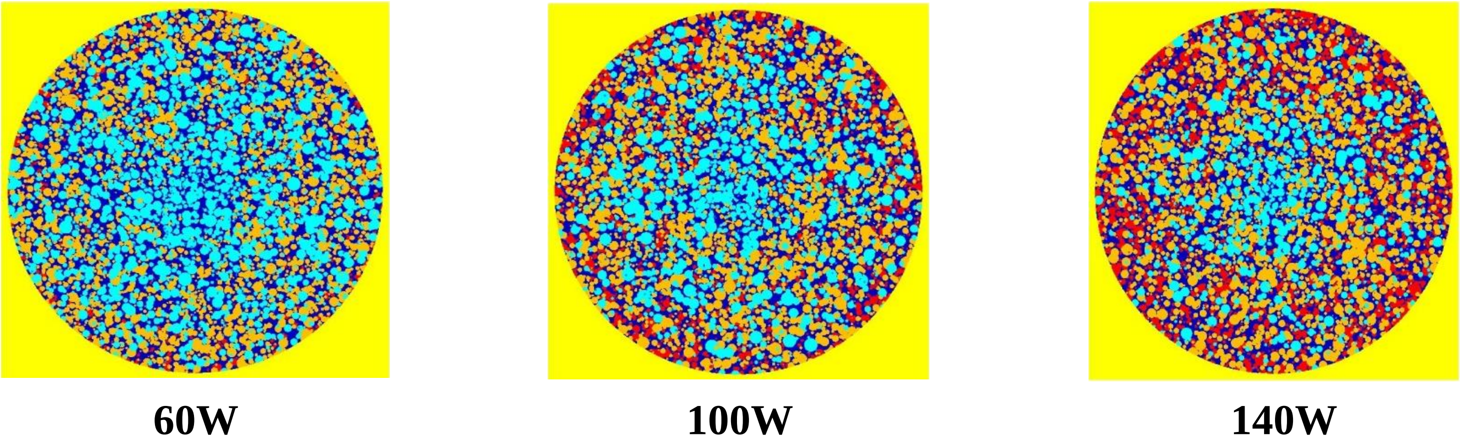
# Monte-Carlo Model - 1

- **Preliminary spray cooling model developed by Kreitzer (2010), uses the time scale estimates described above, & correlations taken from the literature at that time.**
- **This model showed promise, but was unable to make quantitative predictions of the heat transfer rates, or of the onset of CHF. One main output of this model is a video visualization of the spray impact process.**



# Monte-Carlo Model - 2

- **The preliminary version of the model correctly captures the trend of onset of boiling and cavity dry out being initiated near the outer radius of the heater surface. (see below)**
- **Also, the percentages of the heater surface area where boiling occurs and where dry out occurs in cavities before they can be filled in or covered over both tend to increase as the heater power is increased. (see below)**




**Model predictions of heater surface for initial Monte Carlo simulation of 40,000 drop impacts for FC-72, at $Q$ = 1 x $10^{-5}$ $m^3/s$, standoff distance = 13 mm, and $h$ = 50 μm (Kreitzer, 2010). (Dark blue: residual liquid film; teal blue: new impact cavity; orange: onset of cavity boiling; red: dried-out cavity)**

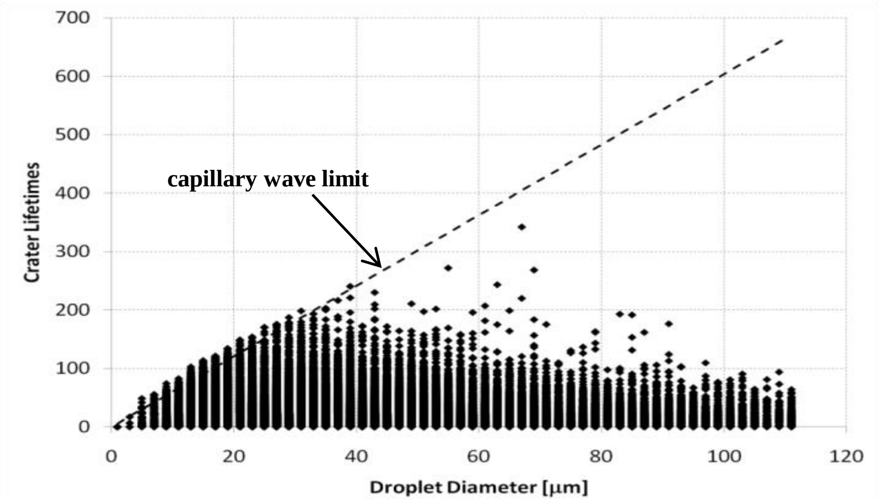
# Monte-Carlo Model - 3

**The model also gives insight into the relative roles of:**

**a) cavity fill-in, and**

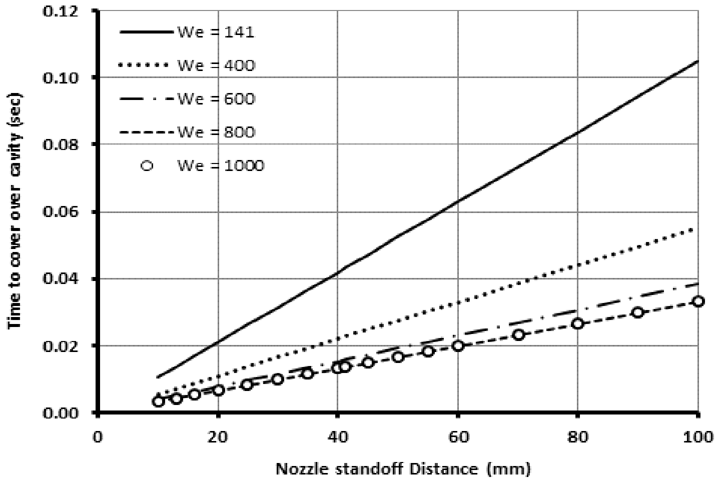
**b) the covering over of cavities due to subsequent droplet impacts.**

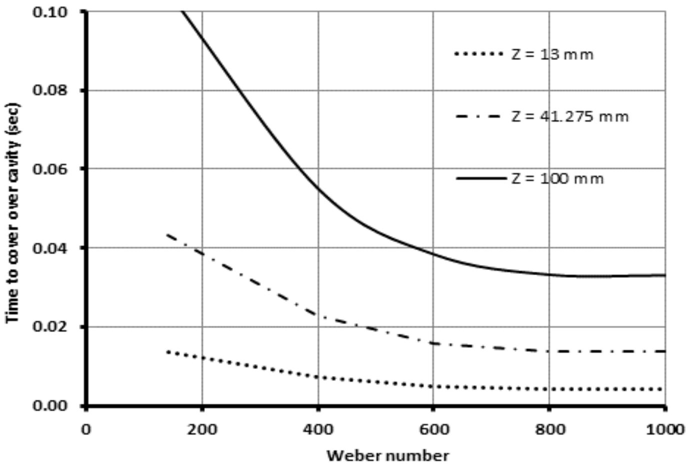
**Droplets of all sizes have a wide range of lifetimes, due to the statistical nature of the spray impact process. However, for the smallest droplets the maximum cavity lifetime is governed by the time for cavity retraction or "fill-in" to occur (for diameters < 38 μm), while for larger droplets, the longest cavity lifetime is predicted to be set by subsequent droplet impacts.**




**Cavity lifetime [$\mu$s] versus drop diameter for initial Monte-Carlo model for FC-72, at $Q$ = 1 x $10^{-5}$ m$^3$/s, standoff distance = 13 mm, $h$ = 50 μm, and heater power = 100 W (Kreitzer, 2010).**

# Time Scales Revisited: Effect of Standoff Distance




- **Results shown are for: <u>water</u> at 20$^o$C subcooling, with Q = 1 x 10$^{-5}$ m$^3$/s, again using an average drop diameter to compute the average time between drop impacts, etc.**
- **The time scale for a cavity to be covered over by subsequent drop impacts decreases for small standoff distances (left plot) and for increasing Weber numbers (right plot).**
- **It is only for a limited range of <u>smaller nozzle standoff distances</u>, and for the <u>larger drops</u>, that the covering over of cavities will be significant in preventing onset of CHF.**

# Future Work

- We plan to improve this initial Monte-Carlo spray cooling model by:
  a.) implementing the recent experimental results that have been summarized in this presentation into the MC model, and
  b.) performing new CFD simulations of single droplet impacts into a static residual liquid layer, but including heat transfer effects.

- Our main goal will be to obtain predictions via CFD of the increased transient heat flux that occurs in the sub-cavity liquid volume, for appropriate ranges of the spray droplet Weber numbers and Reynolds numbers.

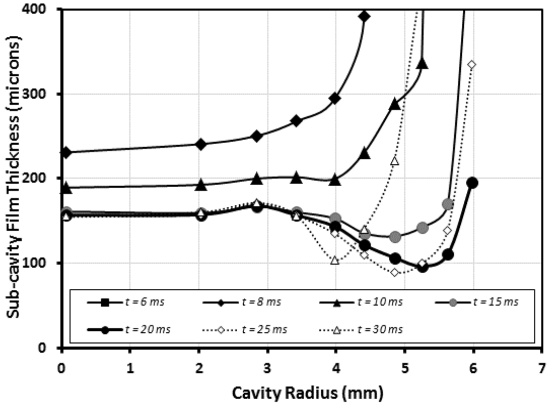
- It is hoped that once this new work has been accomplished, the model will be able to correctly predict the overall heat transfer rates, and the onset of CHF.

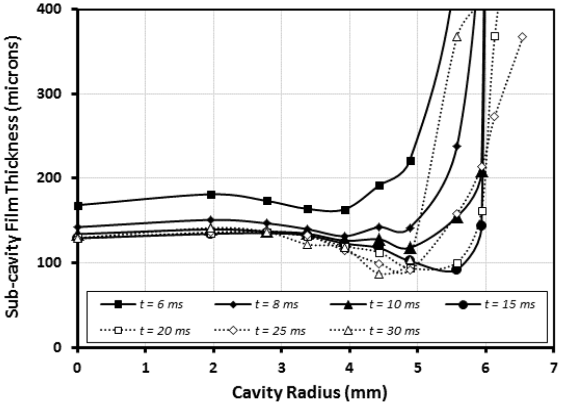
# Questions?

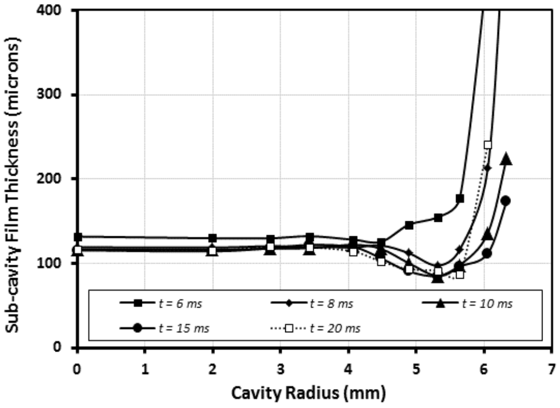
**The author acknowledges the prior support of NASA Cooperative agreement NNX10ANY0YA.**

# Single Drop Sub-Cavity Film Thickness vs. Time & *R*

**We = 410, Re = 2300 (Case 2)**



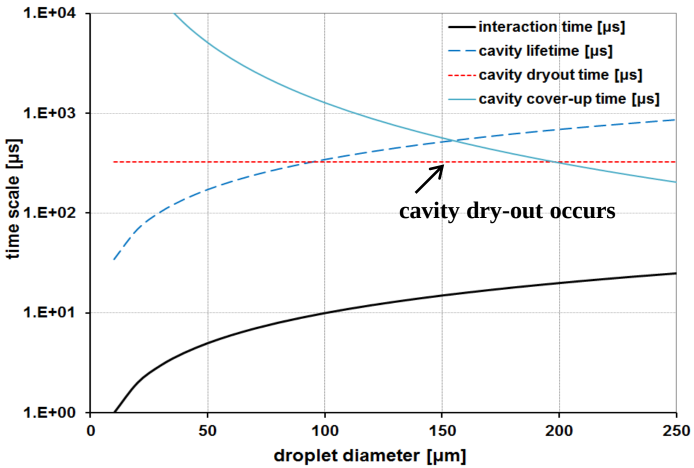



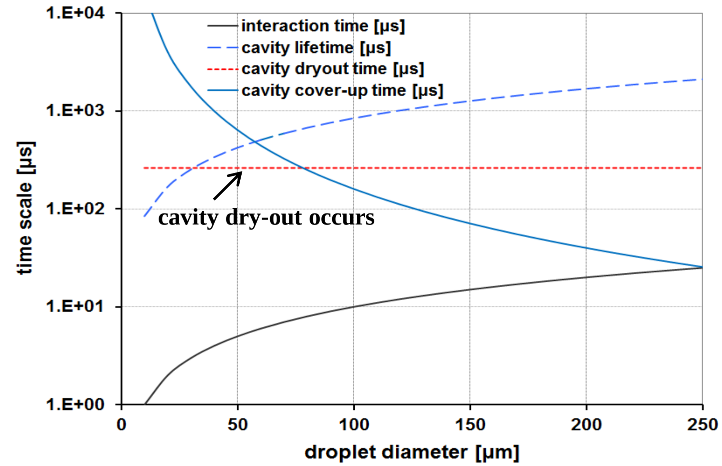

**$h^*$ = 1.0** **$h^*$ = 0.5** **$h^*$ = 0.1**

- **Film thickness data at different radial locations was obtained by traversing the impact surface and liquid tank w.r.t. the droplet generator. Each time history at a different radius is for a different droplet impact experiment, at same diameter and impact velocity.**
- **Small variations from smooth curve vs. *r* are believed to be due to drop-to-drop variabilities.**
- **For all cases, once the minimum centerline film thickness has been reached, the local cavity film thickness is relatively constant for the inner 50-60% of the cavity radius.**
- **But, <u>for all cases, the local cavity film thickness decreases somewhat near inner crown wall</u> at each time, especially at later times shown (during & just prior to crown collapse).**
- **These data have been integrated radially to compute the sub-cavity liquid volume vs. time (Hillen, 2013)**

# Time Scales Revisited: Fill-In, Dry-Out, & Cover-Over




Water, with heat flux = 693 W/cm$^2$

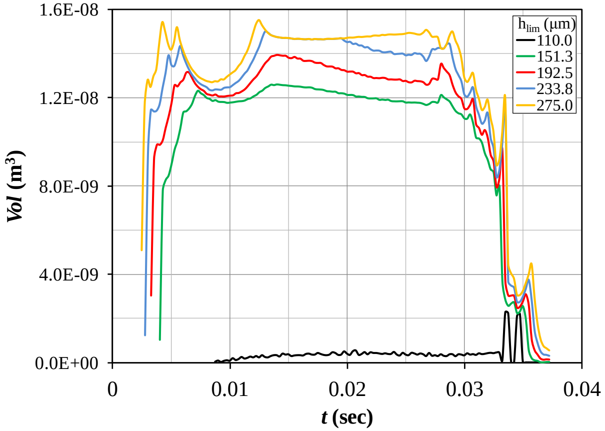



FC-72, with heat flux = 69 W/cm$^2$

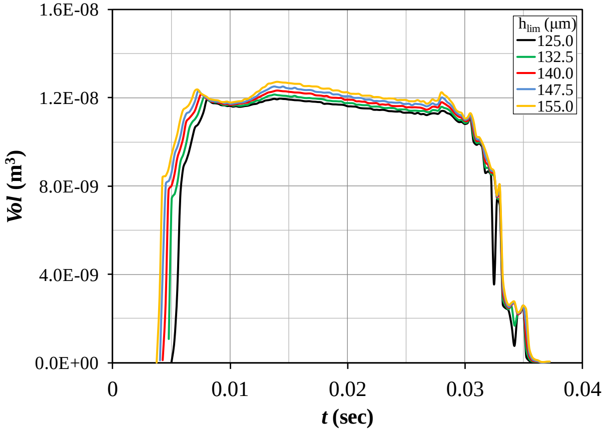
- **Time scales predicted for nozzle standoff distance of 13 mm, at 20°C subcooling, with Q = 1 x 10$^{-5}$ m$^3$/s for water and FC-72; (Earlier AFRL work used this standoff distance.)**
- **Cavities formed by smaller drops are filled in due to capillary action & gravity before drying out.**
- **Cavities formed by the largest drops are covered over by the effects of subsequent nearby droplet impacts before dry out occurs.**
- **The intermediate drop diameters (about 100 – 190 μm for water, & 35 – 80 μm for FC-72) are predicted to dry out before filling in, or being covered over by subsequent drop impacts.**
- **(An average drop diameter was used to compute average time between drop impacts.)**

# Sub-Cavity Volume Calculation Method

## Initial Constraints




## Final Iterated Constraints




- **Integrated across the radial profile of liquid film thickness histories**
- **Where to end radial location?**
  - **Radial limit set by a $h_0$ constraint**
- **Iterative method was used to determine $h_0$ constraints**
  - **Initial constraints: $h_0 = h_{min}$ and $h_0 = 2.5(h_{min})$**
  - **Lower constraint increased to obtain consistent trend with minimal noise**
  - **Upper constraint also lowered to remove noise**
  - **Typically final constraints $1.2(h_{min})$ to $1.6(h_{min})$**
- **Final variation in computed volumes is on the order of 1-2% for $12 \leq t \leq 27.5$ ms**